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A PLAN FOR CERTIFICATION AND RELATED ACTIVITIES FOR THE DEPARTMENT OF ENERGY STRATEGIC PETROLEUM RESERVE OIL STORAGE CAVERNS

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ABSTRACT

In order to comply with state laws, protect the environment, and protect the national investment in oil stored, it is necessary to periodically verify the integrity of the Department of Energy Strategic Petroleum Reserve (DOE/SPR) oil storage caverns. The task of developing plans for cavern certification was a responsibility in Sandia's role of geotechnical support for the SPR program. As an implementation of this task, this report includes a plan and procedures for tests and related activities to evaluate the integrity of the DOE/SPR oil storage caverns.

Acknowledgment

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Introduction

The Department of Energy Strategic Petroleum Reserve (DOE/SPR) has many crude oil storage caverns in salt domes at four sites in the gulf coast area in Texas and Louisiana. In order to comply with state laws, protect the environment, and protect our national investment in oil stored, it is necessary to periodically verify the integrity of these caverns. The task of developing plans for cavern certification was a responsibility in Sandia's role of geotechnical support for the SPR program. As an implementation of this task, this report includes a plan and procedures for tests and related activities to evaluate the integrity of the DOE/SPR oil storage caverns.

Background

Solution mined storage caverns are dynamic. The temperatures of all fluids in the cavern are continually approaching equilibrium with the domal salt. Salt is continuously being leached from the cavern walls, creating new volume and increasing the salinity of the brine. Creep of the domal salt continually reduces the cavern volume. Some insight into these effects and the importance of these changes is obtained by considering the results of a thorough evaluation of SPR cavern West Hackberry 6, Reference 1, as follows.

The 8.6 x 10^6 bbl brine filled cavern was found to have an elasticity of 57 bbls/psi; that is, the injection of 57 bbls of brine caused the cavern pressure to rise 1 psi and the removal of 57 bbls of brine caused the cavern pressure to fall 1 psi. The Department of Energy, Strategic Petroleum Reserve, Project Management Office (DOE SPR PMO) leak rate criterion is 100 bbls/yr of oil, or 0.274 bbls/day from each cavern well (Ref. 2). For the subject cavern, this leak rate from a single cavern well would cause a pressure drop of only 0.0048 psi/day. Such a small pressure decay rate is extremely difficult to measure. Even assuming the measurement of such pressure change rates to be practical, determination of pressure change rates due to thermal, solutioning, and salt creep effects to a similar accuracy would be required before cavern pressure test results could *be* analyzed to determine the part of the measured pressure change rate which was due to leakage.

Temperature surveys of brine in the subject cavern and brine samples from the cavern were taken over a 6 month period. Changes noted in the brine temperature and salinity from these surveys indicated a pressure increase of up to 0.18 psi/day due to fluid temperature increase and a pressure decrease of 0.24 psi/day due to salt solutioning. Although great care and a long time period *were* used to obtain these results, measurement inaccuracies and questions regarding the application of results obtained through wells to average cavern conditions result in significant uncertainties in the effects of temperature and solutioning on pressure. It is clearly not possible to estimate cavern thermal and solutioning effects with sufficient accuracy to determine leaks that are on the order of 100 bbls/yr or less.

The effect of salt creep, the time dependent flow of salt under stressed conditions, is the third factor in cavern dynamics, and it cannot be evaluated to the required accuracies. There are no available in situ experimental techniques which are applicable. Finite element and analytical analyses currently used are generally considered to provide only order of magnitude results which are not adequate for pressure test analysis.

Since it is not practical nor possible with state of the art techniques to evaluate thermal, solutioning, and salt creep effects to the precision required to reduce pressure test results in terms of actual leak rate, it is concluded that cavern pressure tests cannot be used to quantitatively determine leak rates of the order of 100 bbls/yr.

When determination of small leak rates is required, other methods must be used. A reasonable alternative is to leak test the wells entering a cavern. In general, leaks from caverns have occurred near the vicinity of wells where the competent salt has been breached. Thus, determination of leak rates from **all** wells entering a cavern appears to offer the best measurable indication of cavern leakage, though there is some possibility of cavern leakage other than from the wells.

A well leak test can be conducted by filling the wells or well annuli to depths below the casing seats with a fluid lighter (usually nitrogen) than the stored product, and monitoring the interface depth and surface fluid pressure over a period of several days. In reasonable sized boreholes, this test allows the determination of loss rate to an accuracy well within the SPR criterion of 100 bbls/yr of oil, based on the assumption that nitrogen loss rate will be 10 times that of oil (Ref. 2).

Legal Requirements for Cavern Certification Activities

The states of Louisiana and Texas have established legal requirements for assuring the integrity of underground hydrocarbon storage caverns. The portions of these state requirements specifically applicable to cavern certification and recertification activities are detailed below.

From the State of Louisiana, Department of Conservation, Baton Rouge, Louisiana STATEWIDE ORDER 29-M dated July 6, 1977, Section I Safety Inspections under FINDING NO. 5 includes the following:

B. A capacity determination for each storage chamber shall be made and filed with the Commissioner prior to operation of those projects begun after October 1, 1976. The latest available determination for each storage chamber existing on or begun prior to October 1, 1976, shall be verified every five years, or as soon as possible thereafter; but in no event shall this period exceed ten years.

c. A complete inspection of the Christmas tree and casing shall be conducted every five years or as soon as possible thereafter.

FINDING NO. 7 of Statewide Order 29-M is as follows.

FINDING NO. 7

That exception to the guidelines and requirements set forth in FINDING NOS. 4 and 5 should be granted by the Commissioner only upon proper showing by the applicant at a public hearing that such exception is reasonable, justified by the particular circumstances, and consistent with the intent of this order regarding physical and environmental safety and the prevention of waste.

From the Railroad Commission of Texas, Oil and Gas Division, Article 051.02.02.074, RULE 74. UNDERGROUND HYDRO-CARBON STORAGE include6 the following:

(i) Testing.

(1) Each storage well shall be tested for mechanical integrity at least once every five years. The testing shall be in a manner approved by the director.

(2) The operator Shall notify the appropriate district office at least five days prior to testing. Testing shall

not commence before the end of the five-day period unless authorized by the district director.

(3) A complete record of all tests shall be filed in duplicate in the district office within 30 days after the testing.

All SPR cavern certification and recertification activities must comply with the above requirements for the state in which the respective caverns are located. All such activities should be designed to comply with requirements of both states in order to establish a uniform set of certification and recertification procedures for the entire SPR cavern program.

General Guidelines

1. New caverns will be certified for mechanical integrity by testing at the completion of leaching or, in the case of leach fill, and interrupted leach then fill, at the completion of filling.
2. Old caverns will be recertified for mechanical integrity at approximately five year intervals either by retesting or by inference from previous tests and subsequent operational data. The latter option will be technically viable if there is adequate operational data to demonstrate that there are no well integrity problems. In the event that such activities cannot be accomplished at the five year interval, a variance must be requested from the appropriate state agency.
3. Following withdrawal of all or a substantial portion of the oil with fresh water, certification tests of all caverns will be made, regardless of the time interval since previous certification activities.
4. Significant change in the capacity of static oil-filled caverns can be detected by periodic measurements of the oil-brine interface depth, which should increase slowly with time due to thermal expansion of oil and contraction of the cavern volume due to salt creep. When the behavior of such caverns in operation has indicated no reason to question cavern integrity, cavern capacity will be certified at

approximate five year intervals on the basis of original volume stored and periodic oil-brine interface measurements, If there is reason to question cavern integrity, it may be necessary to remove the oil to allow for a sonar caliper log, since a survey tool effective in oil is not presently available.

5. Use of a test including cavern pressurization with brine to maximum test pressure gradient at the shallowest casing seat and a nitrogen well leak test to maximum operating pressure at the shallowest casing seat, as described in Appendix 1, will be used for an initial test of every cavern to meet the requirement for a complete casing inspection under Louisiana Statewide Order 29-M and to meet the test for mechanical integrity under the Railroad Commission of Texas Oil and Gas Division Rule 74. While this test does not include the many and varied casing inspection techniques, it does provide an effective inspection for casing and well integrity. This test will also be used after substantial oil withdrawal from a cavern using raw water, and at any time anomalous cavern operational results indicate the need for a careful cavern evaluation. It will not be used routinely for periodic cavern evaluations at five year intervals unless specifically considered necessary by the DOE 'or the state regulatory agencies.

6. For slick holes and for any well when hanging strings are removed, casing inspection logs will be run in the last cemented casing as practical. such logs will include, but may not be limited to, a multi-arm caliper log and a corrosion analysis log, if such a log is determined to be of value. Inspection of all removed hanging strings will be required. Hanging strings will not be removed for inspection of hanging strings or last cemented casings unless some event or some anomalous cavern behavior suggests it is prudent to do so.
7. Operational data will be collected and analyzed to provide a near real time indication of cavern conditions and to provide baseline data for comparison with nitrogen leak tests. Operational data should include but not be limited to:
   A. Brine pressures (typical daily).
   B. Oil pressures (typical daily).
   c. Oil/brine interface logs (typical quarterly unless cavern pressure behavior indicate need for earlier log).
   D. Fluid temperature logs (typical twice yearly).
   E. Cavern bleeddown data including volumes bled and dates of bleeddown to maintain cavern pressures within acceptable limits (twice-yearly or at such time as the maximum acceptable pressure limit is reached).

8. Caverns with unusual or abnormal configurations will be monitored and or tested using special procedures designed to detect variation from normality. Examples include caverns which are closely spaced or near the dome perimeter, and unusual cavern roof configurations.

9. The Railroad Commission of Texas, Oil and Gas Division will be notified 5 days in advance of any certification related test activities of caverns located in Texas. The state of Louisiana Department of Conservation or the Railroad Commission of Texas, Oil and Gas Division, as appropriate, will be provided statements of certification together with supporting data for each individual cavern.

APPENDIX 1

NITROGEN WELL LEAK TEST

A. WELL PREPARATION AND LOGGING

<u>For Brine Filled Caverns</u>

1. Pull hanging strings from one well if no slick hole is available.
2. Perform a sonar caliper survey of the cavern.
3. Run casing inspection logs in all wells in which there are no hanging strings. Logs will include, but may not be limited to, a multi-arm caliper log and a corrosion analysis log, if such a log is determined to be of value.
4. Blind flange or skillet all connections of surface piping to all wellheads to prevent any surface flow into or out of the wellhead.
5. If one or more of the wells is known to produce gas, take samples of the gas and determine its composition. Measure the rate of gas production on each well during the 48 hours shut in period at maximum operating gradient (see Appendix 1 B, item 3).
6. Install pressure gages on the dead annuli of all wells to possibly provide indication of leakage from the well into the annuli.
7. Perform leak tests of all wellhead hangers.
8. Install an accurate digital pressure recording system on one wellhead.

For Oil Filled Caverns

1. Run casing inspection logs in all wells in which there are no hanging strings. Logs will include, but may not be limited to a multi-arm caliper log and a corrosion analysis log, if such a log is determined to be of value.
2. Blind flange or skillet all connections of surface piping to all wellheads to prevent any surface flow into or out of the wellhead.
3. If one or more of the wells is known to produce gas, take samples of the gas and determine its composition. Measure the rate of gas production on each well during the 48 hours shut in period at maximum operating gradient (see Appendix 1 B, item 3).
4. Install pressure gages on the dead annuli of all wells to possibly provide an indication of leakage from the wells into the annuli.
5. Log the oil-brine interface level in at least one well.
6. Perform leak tests of all wellhead hangers.
7. Install an accurate digital pressure recording system on the oil pressure of one wellhead.

APPENDIX 1

NITROGEN WELL LEAK TEST

B. CAVERN PRESSURIZATION

1. Pressurize the cavern with saturated brine to maximum test gradient. Maximum test gradients and maximum operating gradients established by DOE SPR PMO for the various cavern sites are as shown below. These gradients are defined as pressures at the shallowest casing seat into the cavern divided by the depth from the surface to that casing seat.

Cavern Site	Maximum Test Gradient, psi/ft	Maximum Operating Gradient, psi/f t
Bayou Choctaw	0.85	0.79
Bryan Mound	0.82	0.76
Sulfur Mines	0.80	0.75
West Hackberry	0.86	0.80

   Measure and record the volume of brine injected together with wellhead brine pressure (and wellhead oil pressure if oil filled) as a function of time. Wellhead brine pressure will be measured on a well other than the one through which brine is injected if possible.

2. Shut the cavern in for at least 24 hours and record accurate digital pressure data at time intervals not to exceed 30 minutes. Experience has indicated that a modest and continuously decreasing pressure decay rate can be expected if there is no significant leakage.

3. Bleed off brine until the brine pressure for the nitrogen well leak test is reached. The maximum brine pressure for the well leak test will be that corresponding to maximum operating gradient at the shallowest casing seat if possible, but will in no case exceed the lesser of that corresponding to (1) maximum operating gradient at the shallowest casing seat, (2) maximum wellhead design pressure, typically 2000 psi, or (3) hanging string casing collapse pressure. Measure and record the volume of brine bled off together with wellhead brine pressure (and oil pressure if oil filled) as a function of time.
4. Shut the cavern in for at least 48 hours and record accurate digital pressure data at intervals not to exceed 30 minutes. Experience has indicated that a modest and continuously decreasing pressure increase rate can be expected if there is no significant leak.
5. If one or more of the wells is known to produce gas, take samples of the gas and determine its composition. Measure the rate of gas production on each well during the 48 hours shut in period at maximum operating gradient.

APPENDIX 1

NITROGEN WELL LEAK TEST

C. TEST PROCEDURES

1. Install an accurate digital pressure recording system on each annulus and the hanging string of the well into which nitrogen is to be injected. For wells with no hanging strings a single pressure recording system is required on the wellhead.
2. Rig up a wire line with an interface logging tool on the well into which nitrogen is to be injected.
3. Inject nitrogen into the well if a slick hole or into the annulus if the well has a hanging string. The relatively small volume of nitrogen to be injected in the wells should not substantially affect the pressure in the large SPR caverns. However, nitrogen injection should in no case be allowed to increase casing seat pressures above maximum operating values, to increase wellhead pressures above design values which are typically 2000 psi, or to exceed hanging string collapse pressures. The temperature of nitrogen injected should be at approximately the average borehole temperature determined from logs specified in the "General Guidelines' section. Inject nitrogen until the nitrogen-brine interface is below the casing seat. The final depth of interface below the casing seat should be set about 50 feet if practical but in no case will be

allowed to the depth of the cavern roof. In cases where the borehole is significantly enlarged below the casing seat, the practical limit of the interface depth may be less than 50 feet below the casing seat. During nitrogen injection, record the volume injected as a function of time. After the nitrogen-brine or the nitrogen-oil interface reaches a depth of 300 feet above the casing seat the rate of injection of the rest of the nitrogen is to be held constant. Weigh the nitrogen injected with a system able to measure weight to an accuracy of two pounds or better. Weight of nitrogen injected, pressure, interface depth and time is to be recorded above the casing seat at 10-foot intervals and below the casing seat at time intervals no greater than half the time interval required for the interface to move 10 feet in the casing. These measurements will allow a better estimation of borehole volume below the casing seat than can be obtained from caliper logs. Remove the interface logging tool and shut the wellhead in.

4. Repeat items 1 to 3 for each well into the cavern.
5. After filling the last well with nitrogen, shut in all wells for about 48 hours to allow the nitrogen temperature to approach equilibrium with that of the well. An average nitrogen temperature change of only 1°F during a test in a 2000 foot deep well cased with 13 3/8-inch casing

corresponds to 0.54 bbl volume change, whereas the DOE loss rate criterion for nitrogen is 2.7 bbls/day (1000 bbl/yr) (Ref. 2).

6. During the temperature stabilization period carefully check all wellhead fittings and flanges with soap bubbles, or other suitable means to insure there are no wellhead nitrogen leaks of consequence to the test.

7. During the temperature stabilization period, carefully observe pressures in the annuli and hanging strings for evidence of nitrogen leakage from the annulus into the hanging string. Such leakage is indicated by hanging string pressure having a higher rate of increase with time or a lower rate of decrease with time than the annulus pressure. In the absence of gas temperature effects, each 1 psi decrease in the difference between annulus and hanging string pressure corresponds to a downward movement of 2 feet of the nitrogen-brine interface in the hanging string. A nitrogen leak into the hanging string sufficient to cause a 2-foot per day interface movement in the hanging string is important to the analysis of test results. If the indicated leak corresponds to 2 to 5 feet per day of interface movement, accurately measure the mass of nitrogen leaked during the temperature stabilization period. If the leak corresponds to more than about 5 feet per day of interface movement, connect the annulus and hanging string to each other at the wellhead, and fill both the annulus

and hanging string with nitrogen to the same depth as the annulus was initially filled. In this event a second and comparable length temperature stabilization period is required.

Very accurate pressure measurements are required for detecting difference to an accuracy of 1 psi with annulus nitrogen pressures approaching 2000 psi and hanging string brine pressures hundreds of psi lower. Even if pressures have not indicated leakage into the hanging string at the end of the temperature stabilization period, bleed any nitrogen from the hanging string at the wellhead, and make a judgement as to whether the hanging string should be filled with nitrogen.

8. During the temperature stabilization period, determine the length of time the test of each well should be run. The time selected should be such that a leak rate of about 0.3 bbl/day or 110 bbls/yr can be resolved with the instrumentation used. Using standard wireline interface logging techniques, the best accuracy of interface movement expected is about three feet. The product of this three foot interface accuracy and the volume per foot of the well at depths of interest, from weight measurements of nitrogen injected, yields a volume change uncertainty. An additional factor affecting volume change accuracy is pressure measuring accuracy. Careful pressure measurements

with accurate digital recording systems can be expected to indicate pressure change **over** a typical 1 to 2 week test with an accuracy of 1 to 2 psi. This accuracy, while necessary for diagnostics through the nitrogen temperature stabilization period, is not required for the leak rate resolution of 0.3 bbl/day mentioned above. Pressure measurements with an instrument having accuracy and repeatability of 0.25- percent full scale (such as a good 2000 psi dead weight tester) can be expected to indicate pressure change within 5 to 10 psi. Dividing 10 psi by the well head nitrogen pressure and multiplying by nitrogen volume in the well gives an approximate uncertainty of nitrogen volume change with such 0.25-percent pressure instrumentation. The sum of volume change uncertainty due to measurements of interface movement and measurements of pressure, when divided by the 0.3 bbl/day requirement, gives a minimum number **of** days for length of test, based on measurement accuracies. The length of test should in no case be less than 7 days.

For wells having large boreholes below the casing seat, the length of tests could be reduced by use of more accurate interface change measuring techniques than the conventional wire line, and by more accurate pressure measurements. For wells without hanging strings, the Moorehead TDR interface tool and the AGAR interface tool can be used for more accurate interface measurements in brine filled caverns.

9. At the end of the temperature stabilization period, measure the interface depth in each well for a reference. If the interface depths **are** not satisfactory, it may be necessary to add additional nitrogen. Interface depths may not be satisfactory if they are very near the casing seat and are not satisfactory if they are in the cased hole. If the interface depths are satisfactory, remove the logging tool, bleed all nitrogen from the hanging string (unless the hanging string has been deliberately filled with nitrogen) and shut the well in.

   At the end of the temperature stabilization period, it would be reasonable, if significant cost savings would result, to begin using pressure measuring instrumentation having errors no greater than 5 psi.

10. Record all pressures **at** appropriate time intervals for the length of time determined in item 8. Appropriate time intervals could be **as** small **as** 30 minutes for an automatic **digital recording** system but should **never** exceed 24 hours, even for manual **readings** with **a** system such **as a** dead weight tester. Monitor these pressures for indications of pressure **changes that** may **indicate a significant well leak or any anomalous cavern behavior.**

11. For wells with hanging strings which were not filled with nitrogen, bleed off and measure the volume of nitrogen accumulated in the hanging string during the test.
12. Measure final interface depths in all wells.
13. Calculate the weight loss of nitrogen from the well and determine the volume at initial density corresponding to this weight loss. Divide this volume by the number of days between the reference and final interface depths for a nitrogen volume loss rate. The initial weight of nitrogen in the well is:

$$W_o = 144 \frac{KP_oV_o}{RT_o} \tag{1}$$

The final weight of nitrogen:

$$W_f = 144 \frac{KP_fV_f}{RT_f} \tag{2}$$

And the initial density of nitrogen in the well is:

$$\rho_o = 144 \frac{KP_o}{RT_o} \tag{3}$$

where

ρ density, lbs/ft^3

W weight, lbs

P wellhead pressure, psia

V volume, ft^3

R gas constant, 55.16 ft/°R for nitrogen

T average temperature, °R

(Can be assumed constant in the absence of gross interface movements)

K ratio of average pressure in the well to measured wellhead pressure (can be assumed constant in the absence of gross interface movements or gross wellhead pressure changes)

Subscript $_o$ refers to conditions at time of initial interface

Subscript $_f$ refers to conditions at time of final interface

Subtracting the final weight (2) from the initial weight (1) and dividing by the initial density (3) yields a volume loss at initial density, (ΔV_{id}),

$$\Delta V_{id} = V_o \left(1 - \frac{P_f V_f}{P_o V_o}\right) \qquad V_o \left(- \frac{\Delta P}{P_o} - \frac{\Delta V}{V_o}\right) \tag{4}$$

where

$$P_f = Po + AP$$

$$V_f = Vo + AV$$

The above applies to the simplest case where nitrogen does not leak from the annulus into the hanging string and where significant gas production during the test is not expected. For the case with nitrogen leaking from the annulus into the hanging string, the leaked nitrogen is not lost from the well. The well leakage is calculated by reducing the weight loss calculated from Equation (1) and Equation (2) by the weight leaking into the hanging string as determined in Step 11.

For the case of gas production at test pressure, the volume loss of nitrogen from the well is partially compensated by the gas entering the well during the test. An approximation of the nitrogen weight loss is obtained by adding to the difference between Equations (1) and (2), the value of $W_G(R_G/R_N)$, where the subscript G indicates the gas produced by the well, and N indicates nitrogen. This approximation corresponds to the assumption that the measured gas produced, W_G, is added to the nitrogen at the time of the final interface and immediately results in a uniform gas mixture at the temperature of the nitrogen.

14. Evaluate leak test results to determine whether measured nitrogen leaks are large enough to try to locate and fix. For a nitrogen loss rate of less than 1000 bbls/yr from any single well, the oil loss rate will be assumed less than 100 bbls/yr and the well will be judged acceptable. For nitrogen loss rates greater than 1000 bbls/yr, additional nitrogen leak tests as described in Ref. 2, will be made to allow a more precise estimate of nitrogen to oil loss ratio for the specific leak, and also to locate the leak. If these additional tests indicate an oil leak rate greater than 100 bbls/yr, a decision will be made by DOE/SPR/PMO whether to repair. If a decision is made not to repair, steps will be formulated to insure that the leak rate does not continue to increase at an unacceptable rate.
15. Digital pressure measuring systems will be calibrated on site before installation for the test and following removal from the test.

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